ascertain whether the iron-manganese alloys, which are non-magnetic at atmospheric temperature, become magnetic by so doing.

2. With a view to the desirability of testing not only after, but also during immersion in liquid hydrogen, an apparatus has been constructed, which makes it possible to test the samples quickly one after another at a temperature of 20° K., with as little loss of hydrogen as possible.

3. The iron-manganese alloys, containing the higher percentages of manganese, cannot be made magnetic at atmospheric temperature by cooling to the boiling point of liquid hydrogen or liquid helium.

4. The existence of one magnetic and one non-magnetic, or at most slightly magnetic, manganese-iron compound is shown to be probable, and the non-magnetic properties of the higher manganese-iron alloys may be explained by their means.

The Hardness of Solid Solutions.

By Walter Rosenhain, B.A., D.Sc., F.R.S. (of the National Physical Laboratory).

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It is a well-known fact of metallurgy that the addition of one metal to another produces an increase of strength and hardness. In some alloys, this change of properties is accompanied by the formation of a new micro-constituent or phase, which is itself harder, and also, as a rule, more brittle than either of the constituent metals. In a very large and important group of alloys, however, the addition of the second metal, up to certain limits of concentration, does not lead to the formation of a second phase or constituent. Alloys of this type, when they have attained an equilibrium condition, consist of an aggregate of polyhedral crystals, homogeneous in composition so far as their micro-chemical behaviour indicates, and in most respects entirely similar to the constituent crystals of the pure metal, which forms the basis of the alloy. A typical example of this kind is furnished by the alloys of copper with zinc, containing up to about 30 per cent. of zinc. Alloys of this type are generally described as "solid solutions," on the ground that the state of intimate mixture which exists in the liquid (molten) solution of the two metals in one another is preserved in these alloys after solidification. In Continental language, such crystals are more frequently termed "mixed crystals" ("Mischkrystalle"), but the present author prefers to avoid this term on account of a possibly misleading interpretation.

A further fact in connection with metallic solid solutions is also well known, but appears to require explanation. A solid solution alloy is always harder and stronger than the pure metal of which it mainly consists, and frequently this difference in physical properties is very marked. Thus, annealed pure copper has a Brinell hardness number of 36, and a tensile strength of about 13 tons per square inch. An alloy of copper containing 30 per cent. of zinc in solid solution, on the other hand, in the corresponding annealed condition, has a Brinell hardness number of 57, and a tensile strength of 20 tons per square inch. It is the purpose of the present paper to suggest an explanation for this hardening and stiffening effect of the added metal in solid-solution alloys, and to show that this explanation leads to an inference which is in striking accord with well-known facts.

The explanation of the properties of solid-solution alloys which is put forward in the present paper is based upon a conception of the manner in which two metals may crystallise together in the form of solid-solution crystals. As a result of the X-ray analysis of crystal structure, mainly carried out by Sir William H. Bragg and W. L. Bragg,* and by A. W. Hull,† it is now known that, in a metallic crystal, the atoms of the metal are arranged in certain definite ways on a space-lattice, and that this arrangement may differ in detail from one metal to another, not only in regard to the nature of the lattice (cubical or otherwise) and the occupied points, but also in regard to the normal inter-atomic distance or spacing of the lattice. On the view now put forward, the crystals of a solid solution of metal B in metal A are built up on the same space-lattice as crystals of pure A, the sole difference being that a certain number of individual atoms of A are replaced by atoms of B. It is obvious that the extent to which such an arrangement will be possible must depend upon the relation which exists between the atoms of the two metals. If both tend to take up a similar space-lattice arrangement, and if their normal inter-atomic distances do not differ very much, a single crystal may be built up, upon the normal space-lattice arrangement of A, using atoms of A and B indiscriminately, up to a considerable proportion of B. If the similarity of the two kinds of atom is sufficiently great, then such an indiscriminate construction might easily be conceived as being possible in all proportions between the two kinds of atom. In that case, we should expect to find that the two metals could form homogeneous solid solutions when alloyed in any proportion ranging from pure A to pure B. Such cases are, of course, well known among pairs of very similar metals, such as iron and nickel or silver and gold.

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* W. H. and W. L. Bragg, 'X-rays and Crystal Structure,' p. 173.

† A. W. Hull, "A New Method of Chemical Analysis," 'J. Amer. Chem. Soc.,' 1919.

Where the similarity, in regard to crystalline habit and arrangement, of the two kinds of atom is less complete, it would be anticipated that, up to a certain concentration at either end of the series, the atoms would be built together indiscriminately upon a single space-lattice, but that, beyond certain limits of concentration, the two kinds of atoms would become segregated into two kinds of different crystals, thus giving rise to a duplex structure of two distinct kinds of crystals, each consisting of saturated solid solution of one metal in the other. The degree of dissimilarity of the two kinds of atom would determine the exact concentration at which this separation occurs, and we would thus expect to find in metallic alloy systems all gradations, ranging from complete mutual "solid" solubility down to almost complete insolubility in the solid state; it is, of course, well known that such gradations are found among known alloys.

From the present point of view, however, interest centres on the determining factor which governs the limiting solid solubility of metal B in metal A. If the view of the structure of a solid-solution crystal indicated above is correct, it follows that the actual arrangement of the atoms on the space-lattice typical of metal A cannot exist entirely undisturbed when some of the atoms of A are replaced by atoms of B. The forces acting on any atom of A, for instance, when one of its neighbours in the lattice is an atom of B, cannot possibly be the same as those acting on an atom of A entirely surrounded by atoms of A; there must thus be some want of symmetry in the forces acting on an atom so placed, with a result which is perhaps best expressed by saying that such an atom will be pulled slightly out of its proper place, *i.e.*, that the space-lattice will be slightly distorted at such points. Now, it is evident that such distortion must affect the internal energy of the whole system, and this effect must increase with the increase in the amount of distortion which accompanies the presence of a larger number of atoms of B. A point will therefore be reached when the energy-content of the system as a whole will be less if the atoms of B are separated and arranged on a space-lattice of their own. Such an arrangement implies the existence of boundaries between two different kinds of crystal and the accompanying storage of energy in such boundaries, and it is the balance between the energy-content of the two geometrically possible types of arrangement which must determine the limiting concentration of the solid solution in each case.

With a full knowledge of the forces at work between adjacent atoms it would be possible to calculate the limiting concentration of any solid solution from the character of the constituent atoms; in the present state of our knowledge, all that can be said is that the greater the extent to which the space-lattice is distorted in the neighbourhood of "dissolved" atoms (atoms of "B") the lower will be the limit of solid solubility of B in A. During the process of formation of such a solid solution, a great deal must depend upon the uniformity with which the atoms of B are distributed through the space-lattice. If there is a concentration of the dissolved atoms in any region, then there must be a tendency for rearrangement to occur with a view to arriving at some symmetrical arrangement which shall correspond to the minimum energy-content. If such a distribution is really symmetrical, then an interesting result must follow, viz., that in a solid solution which has been allowed to attain equilibrium conditions, the dissolved atoms will be distributed through the crystals in such a way as themselves to constitute some sort of space-lattice of their own. This is a conclusion which is capable of experimental verification by means of X-ray analysis; when the result is obtained, however, it will be important to realise that the existence of such a secondary space-lattice arrangement of the dissolved atoms (B) does not imply the existence of separate crystals of B. The further question of how far a solid solution which has attained such a state of symmetrical arrangement approaches to the character of a chemical compound need not be discussed here.

The most important conclusion which emerges from what has been said above is that the "solid solubility" of metal B in metal A will be, to a first approximation, inversely proportional to the amount of distortion of the normal space-lattice of A caused by the substitution of an atom of B for an atom of A in that lattice. The importance of this consideration lies in the fact that this amount of distortion of the space-lattice of A by the presence of B also governs certain of the physical properties of the resulting alloy, particularly the hardness of the material and its resistance to mechanical deformation generally.

It is now well recognised that the ductility of metals, *i.e.*, their power of undergoing plastic deformation without rupture, resides in their essentially crystalline character. Plastic deformation takes place within the crystals of metals by a process of slip, occurring on gliding or cleavage planes,* whereby the crystals accommodate themselves to the new shapes forced upon them by the deformation of the mass. It is precisely the power of the crystals to undergo such slip which governs the ductility of the metal, and their power of resisting slip which determines their power of resisting deformation. If this view is correct, then anything which tends to hinder the free occurrence of slip on the principal planes of a crystal will increase the hardness (or power of resisting deformation) and will lower the ductility of the material. The application of any appreciable amount of plastic deformation (or "cold work") is known to act in this manner, and does so, according to the views of Beilby,* by the partial destruction of the crystalline arrangement of the atoms within the crystals.

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* Ewing and Rosenhain, 'Phil. Trans.,' A, vol. 249 (1899).

The view which it is desired to put forward here is that any even slight distortion of the space-lattice of the crystals of a metal by the presence of "dissolved" atoms of another metal, in the manner indicated in the earlier part of this paper, must serve as a hindrance to slip on the crystal planes. Strictly speaking, in fact, the crystal "planes" have ceased to exist in such a slightly-distorted crystal. The very facility for slip which renders metallic crystals soft and ductile depends upon the smooth regularity with which the atoms are arranged on their space-lattice, and if this smoothness is lessened by the slight distortion of the lattice, it is obvious that slip will be rendered more difficult, and this difficulty will increase, to a first approximation, proportionately to the amount of distortion existing in the space-lattice.

Combining this last inference with the one already drawn above in regard to the factor governing the limiting solid solubility of one metal in another, we arrive at the following conclusion: that since the amount of distortion which the introduction of a given "dissolved" atom produces in the space-lattice of the solvent metal governs both the limiting solubility of the dissolved metal and the degree of hardening produced in the solvent metal, we should expect to find that *the hardening effect of one metal upon another in the form of a solid solution* should, to a first approximation be *inversely proportional to its solid solubility.*

This very general conclusion, which—so far as the author is aware—has not been previously stated, appears to be in good general agreement with experimental fact. There are, in the first place, a certain number of binary alloy systems which consist of unbroken series of solid solutions. In some of these, of which gold-silver and iron-nickel are good examples, the shape of the liquidus curve suggests that the two kinds of atoms are very similar, since the alloys solidify in a manner closely approximating to that of a pure metal. In these cases there is very little hardening effect of one metal upon the other. The alloys of copper and nickel also form a series of unbroken solid solutions, but their freezing range is distinctly larger, so that the alloys depart further from the behaviour of pure metals. Here, where there is thus some evidence of slightly greater dissimilarity between the atoms, there is a distinctly greater hardening effect. Finally, in the case of the alloys of copper with manganese we have an alloy system still forming what appears to be an unbroken series of solid solutions, but the shape of the freezing point curve suggests that the system is one in which the series of solid solutions has only just been maintained and that a very slightly greater divergence between the component atoms would have led to the occurrence of a short range of duplex alloys. Here a still greater degree of hardening is found than in the systems previously mentioned.

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* Beilby, "The Hard and Soft State in Metals," 'Phil. Mag.,' August, 1904; also 'Roy. Soc. Proc.,' A, vol. 76, p. 462 (1905), and 'Roy. Soc. Proc.,' A, vol. 79 (1907).

Still more striking evidence in support of the generalisation stated above is to be obtained from a consideration of alloy systems in which the range of solid solutions is definitely limited. Unfortunately, the ranges of solid solubility for alloys in true equilibrium have only been determined with sufficient accuracy in a comparatively few instances, while a detailed knowledge of the corresponding mechanical properties is also lacking in many cases. For the alloys of copper and for those of aluminium, however, adequate data are available. In regard to copper, the alloys with nickel and manganese have already been mentioned. In the well-known alloys of copper with zinc (brass, etc.), solid solutions can be obtained at the copper end of the series containing up to about 36 atomic per cent. of zinc (equivalent to about 37 per cent. of zinc by weight). The corresponding limit for aluminium in copper lies at about 14 atomic per cent. of aluminium (corresponding to about 7 per cent. by weight), while, for tin in copper, the limit lies near 6·7 atomic per cent. (equivalent to 12 per cent. by weight). In good correspondence with these figures are the facts concerning the hardening effects of these three metals on copper. It is difficult to give exact quantitative data, since tests on the alloys in a strictly comparable condition are not readily available, but there can be no doubt that the hardening effects of the three metals are distinctly in the inverse order of their limiting solid solubilities expressed in atomic percentages, as given above. Thus the well-known brass, containing 70 per cent. (by weight) of copper and 30 per cent. of zinc, is still very ductile. The ductility of the alloys of copper with aluminium decreases rapidly after an aluminium-content of 7 per cent. has been passed, while, in the case of the copper-tin alloys, an addition of 4 per cent. of tin (by weight) almost exhausts the ductility of the material. It appears probable, again to a first approximation, that the saturated solid solutions of copper containing any of the soluble metals will have approximately similar mechanical properties, independently of which metal has been used to bring about saturation. Since, however, the solubilities in some cases are high, the physical properties of the dissolved metal itself must affect such a conclusion, which is none the less broadly in conformity with the facts.

Similar evidence is to be obtained from a consideration of the alloys of aluminium with zinc and copper. In the aluminium-zinc series, solid solutions containing above 15 atomic per cent. of zinc (equivalent to a little under 30 per cent. of zinc by weight) can be obtained, while, in the aluminium-copper series, the limiting solid solubility lies in the neighbourhood of 1·5 atomic per cent. of copper (about 4 per cent. by weight). In conformity with this difference in solid solubility, we find that the hardening effect of copper on aluminium is very much greater than that of zinc. Actually, it is much more difficult, on account of slower diffusion, to obtain really saturated solid solutions of copper in aluminium than of zinc, but, when saturation with copper has been obtained, it is found that the physical properties of the resulting alloy (containing about 4 per cent. of copper by weight) are not very different from those of a solid solution of zinc in aluminium containing about 30 per cent. (by weight) of zinc.

Reference may further be made to the alloys of iron. The solid solubility of carbon in γ-iron is of the order of 2 per cent. by weight. In accordance with this figure, we find the enormous influence of carbon on the physical properties of iron, as compared with the effects of the highly soluble elements, such as nickel or silicon.